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Optimization of Mesophilic Anaerobic Digestion using Bio-Vegetable Waste for Emerging Pollutant Removal

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Vegetable waste is one of the emerging pollutants generated heavily in market areas. Many vegetable wastes are dumped in waste pits as they are unsuitable for animal feed. Consequently, a high amount of waste is generated globally from these sources. Such emerging pollutants must be removed by finding alternative uses. This work examines methane generation from vegetable wastes (bio-waste) under the mesophilic temperature range of 18-37°C. The anaerobic process is carried out within this temperature range over a 30-day hydraulic retention time using a floating dome anaerobic digester with continuous digestion. Using neural networks (ANN), response surface methodology (RSM) and artificial intelligence (AI), the primary goal of the study is to assess and maximize methane and biogas production from vegetable wastes at various slurry temperatures, organic loading rates, pH levels and hydraulic retention times. The experimental results indicated that the optimal conditions were a mesophilic temperature of 14.71°C, OLR of 0.27, pH of 6.12 and HRT of 28 days, achieving biogas production of 1.875 m³ and CH_4 percentage with a desirability of approximately 0.95. When comparing the biogas and methane (CH_4) experimental values with the predicted ones from ANN and RSM, there is strong agreement between the predicted and experimental results.

KEYWORDS

Biogas, Methane, Mesophilic, Hydroretention time, Emerging pollutant

1. INTRODUCTION

Clean technology recommends use of waste to create useful products by applying novel scientific methods and advanced technologies. Vegetable waste contains emerging pollutants, like plant hormones and they must be used as raw materials for energy generation, which involves removing these pollutants. This is the focus of this manuscript. Biogas and methane are environmentally friendly green fuels used for cooking, boiling liquids, processing solid foods, transportation and power generation. Basically, biogas contains 40-56% methane (CH_4), 35-45% carbon dioxide (CO_2) and small amounts of hydrogen, nitrogen and other impurities. Biogas can be produced economically on both small and large scales, making it possible to tailor production to meet regional and national energy needs, as well as the gas requirements of rural and urban areas [1]. More recently reports that in the developed world, biogas technology is advanced and used as a vehicle fuel and for generating clean electricity [2]. It has been utilized as a renewable and alternative energy source for various purposes, including home heating, lighting and cooking.

Biomethanization, also known as anaerobic digestion, is a process where organic matter ferments in absence of oxygen, converting through bacteria into biogas (mostly CH_4 and CO_2) and producing a fertilizer rich in mineral nutrients, which is immediately available for plants. Hemadri *et al.* (2022) explains that organic matter is fermented through this microbiological process, transforming it into biogas and a nutrient-rich fertilizer [3]. Sathish *et al.* (2019) states that biogas is generally produced through the biological decomposition of organic wastes, such as municipal solid waste, animal

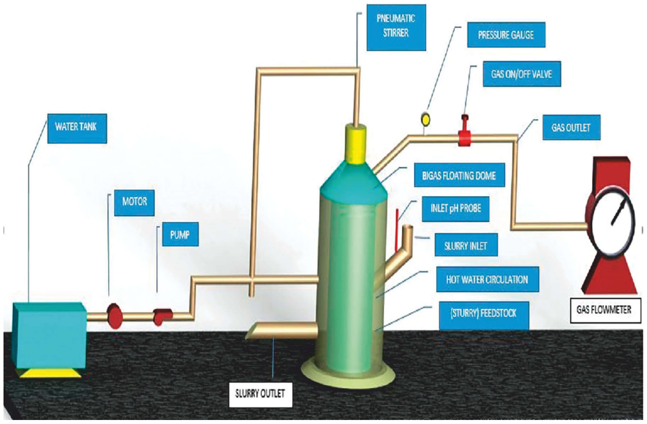

Figure 1. *Arrangement of an experimental set*

waste, plant waste, vegetable waste and kitchen waste, all in the absence of oxygen through anaerobic digestion [4]. Vegetable waste can be converted into energy in the form of methane and biogas, which helps address issues caused by its high water content, such as illness transmission and bad odours. Vegetable waste produces two useful gases, methane and hydrogen, which generate electricity and heat, provide fuel for cooking and can power vehicles. Caruso *et al.* (2019) notes that anaerobic digestion (AD) plays a vital role in recovering energy from various organics and in recycling nutrients during the digestion process [5]. Different types of bacteria breakdown organic materials in stages during anaerobic digestion, which occurs through simultaneous reactions [6]. Large bacterial populations grow and facilitate the three key processes: hydrolysis, acidogenesis (acid production) and methanogenesis (methane formation).

Anaerobic digestion is one method of vegetable waste valourization that has developed rapidly over the past ten years [7]. For different methods of valourization to be successful, many factors must be optimized. For instance, the design of the system, alongwith physical and chemical properties of feedstock, such as moisture, volatile solids, nutritional composition, pH and particle size - affect the efficiency of anaerobic digestion and biogas production [8,9]. Composting is greatly influenced by the C:N ratio and nutrient levels. High-fat vegetable waste takes longer to compost because micro-organisms find it harder to breakdown. The wide variety of vegetable wastes from different sources and types is one of the main challenges in recycling vegetable waste [10,11]. Although many waste conversion technologies are available, little is known about the composition of various vegetable waste types and their potential as feedstocks for different technologies [12]. Digesters often called biodigesters, are sealed reactors that facilitate anaerobic digestion by providing an environment free of oxygen for responsible microorganisms. The main goal of this work is to evaluate and maximize methane and biogas production from vegetable waste through mesophilic anaerobic digestion. This study aims to determine optimal mesophilic temperature, organic loading rate (OLR), pH and hydraulic retention time (HRT) for maximizing biogas and methane output, as well as to utilize artificial neural network (ANN) and response surface methodology (RSM) models to predict biogas and methane production, comparing these predictions with experimental data to verify their accuracy and reliability.

2. MATERIAL AND METHOD

The emerging pollutant of vegetable waste used for this study was collected from a Koyambedu market, while fresh cow manure was obtained from a cow farm near the Koyambedu market. A 1 m^3 anaerobic digester was used for this study with two different temperature ranges. Anaerobic digestion stored with fresh cow manure served as a starter, combined with mixed vegetable waste in a ratio of one part waste to 1% water added for digestion periods. Figure 1 shows the arrangement of experimental setup. The continuous anaerobic digestion operated under two temperature conditions: mesophilic and thermophilic, within range of 28-45°C. The vegetable waste is soaked in a plastic water bath overnight to partially decompose with help of microorganisms and organic loading rate (OLR). Vegetable waste is loaded into a floating dome anaerobic digester with a 30-day hydraulic retention time (HRT) under two temperature conditions. These experiments are conducted in two phases: one mesophilic and the other thermophilic. Both phases last only 30 days after HRT. During both phases, biogas production and methane percentage are measured throughout the 30 days. The pH range of vegetable wastes in digester was recorded during the digestion periods. This is carried out in two phases at the point of feeding the digestate.

Temperature is measured using a digital thermometer with a thermocouple inside the digester. The pH is noted with a pen-type pH redox meter during digestion of the slurry. Methane and biogas are measured using gas chromatography at the Nagapattinam Petrochemical Limited (NPL). Temperature readings are taken daily between 11 pm and 2 pm throughout both phases. Gas samples are collected in airbags from the digester for testing and analysis. Mesophilic temperature, OLR, pH, agitation time and HRT are considered input parameters

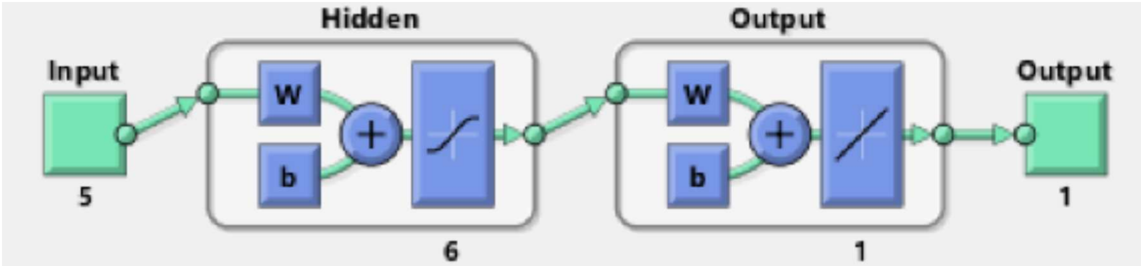

Figure 2. *Architecture of a 3 layer artificial neural network*

Table 1. *ANOVA for biogas*

Sources	Sum of square	Df	Mean square	F-values	p-values (Prob.>F)
Model	1.1425	20	0.0571	201.0485	<0.0001
A	0.004	1	0.004	14.0364	0.0046
B	0.0008	1	0.0008	2.7869	0.1294
C	0.0003	1	0.0003	0.9716	0.35
D	0.0024	1	0.0024	8.3021	0.0181
E	0.0077	1	0.0077	26.9481	0.0006
AB	2.50E-07	1	2.55E-07	0.0009	0.9767
AC	1.80E-05	1	1.41E-05	0.0499	0.8282
AD	0.0012	1	0.0012	4.0853	0.074
AE	0.0044	1	0.0044	15.38	0.0035
BC	7.35E-05	1	7.13E-05	0.2511	0.6283
BD	0.0024	1	0.0024	8.3714	0.0178
BE	0.0028	1	0.0028	9.7741	0.0122
CD	0.0003	1	0.0003	1.1004	0.3215
CE	0.001	1	0.001	3.3569	0.1001
DE	0.0036	1	0.0036	12.5518	0.0063
A^2	0.0009	1	0.0009	3	0.1173
B^2	0.0015	1	0.0015	5.2329	0.048
C^2	0.0002	1	0.0002	0.5459	0.4788
D^2	0.0001	1	9.86E-05	0.3303	0.5796
E^2	0.0013	1	0.0013	4.4889	0.0632
Residual	0.0026	9	0.0003		
Cor total	1.1450667	29			
R^2	0.9978				
Adj. R^2	0.9928				

in this study, while biogas and CH_4 are output parameters. The experimental plan involved 30 experiments based on response surface design, with data collection for each. It consists of several interconnected processing units called neurons that work together to address a specific issue simultaneously. Figure 2 shows a three-layer artificial neural network (ANN) architecture. Some parameters fed into the system include mesophilic temperature, pH ranges, organic loading rates, HRT and agitation time. The neuronal outputs are biogas and CH_4. Using 30 sets of experimental data and the back propagation technique, input and output values were trained and validated.

3. RESULT AND DISCUSSION

In this study, biogas was generated from vegetable wastes, which are considered an emerging pollutant. The observations were recorded. Various input variables were considered for biogas and CH_4 production. The RSM methodology involved 30 experiments, which were also used as training trials in this study. The developed mathematical model equations fit with experimental values and variance analysis (ANOVA) was used to determine the significance of the model coefficients. The F-value of 201.05 in table 1 indicates that the model is significant. Only 0.01% of such a high model F-value can be attributed to noise. When prob.>F is less than 0.0500, it means the model terms are important. In this case, msophilic temperature is an important model term. If the value is greater than 0.1000, the model terms are considered irrelevant. There is a strong agreement between the predicted and observed values, with R^2 values of 0.9658 and 0.9928, respectively. The software calculates the Adeq. precision, which measures the signal-to-noise ratio. An ideal ratio is greater than 4; with a ratio of 48.737, the signal is strong enough [13]. This model is helpful for navigating the design environment.

$$\text{Biogas} = +23.89+0.055A+6.6B-7.8+0.46D-0.252E+0.018AB-0.0166AC-5.68AD-4.5e^{-3}AE+3.35BC+1.89BD+0.46BE-0.105CD+0.04CE+2.66e^{-3}DE+2.3e^{-3}A^2-10594B^2+0.6+C^2-202e^{-3}D^2+8.7e^{-4}E^2 \quad ...(1)$$

The biogas response surface contour plot is shown in figure 3. Here, the biogas is at a minimum organic loading rate and in figures 3a,b, biogas reaches a maximum at a steady organic loading rate [14]. Figure 3c shows that the biogas concentration increases while the agi-

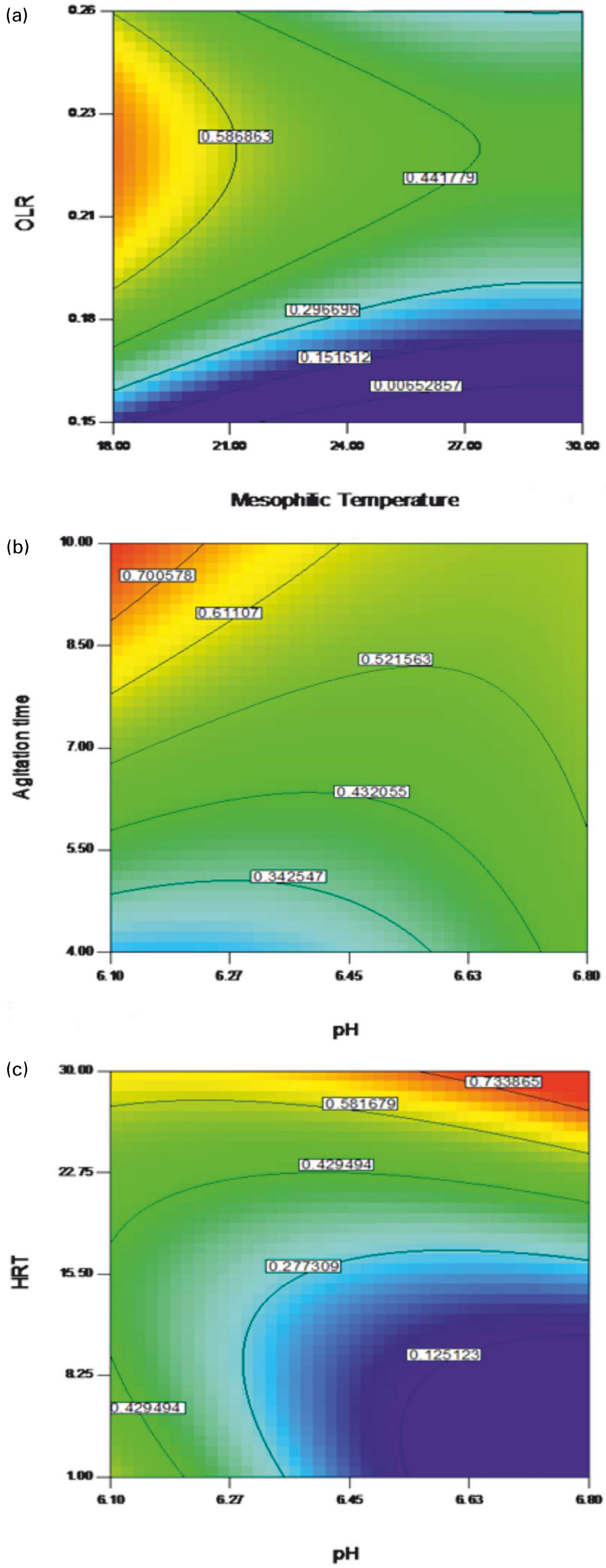

Figure 3. *Biogas RSM contour graph*

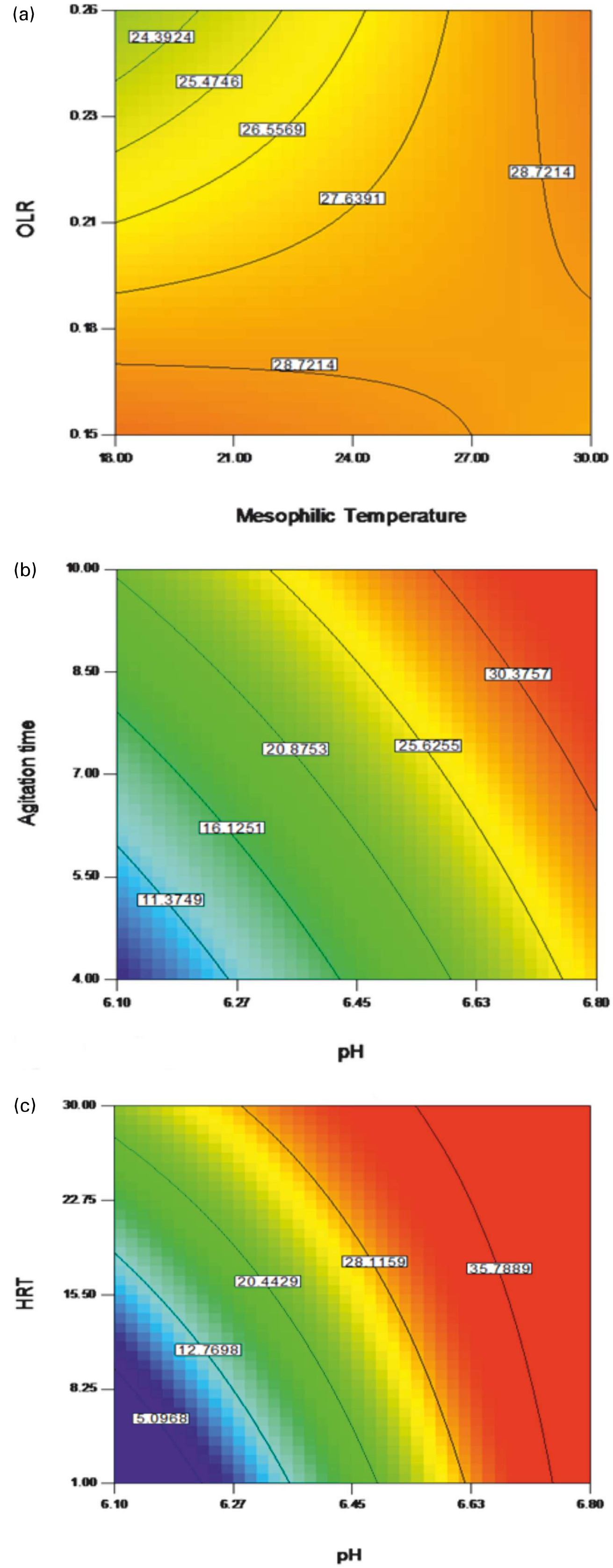

Figure 4. *Methane RSM contour graph*

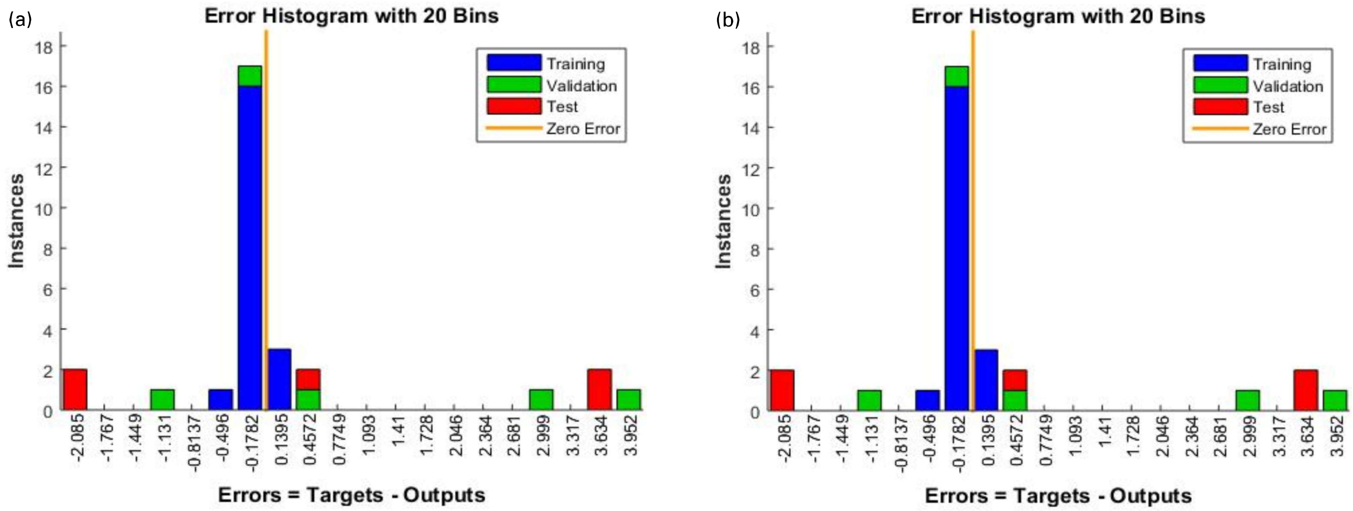

Figure 5. *ANN model errors for (a) biogas and (b) methane*

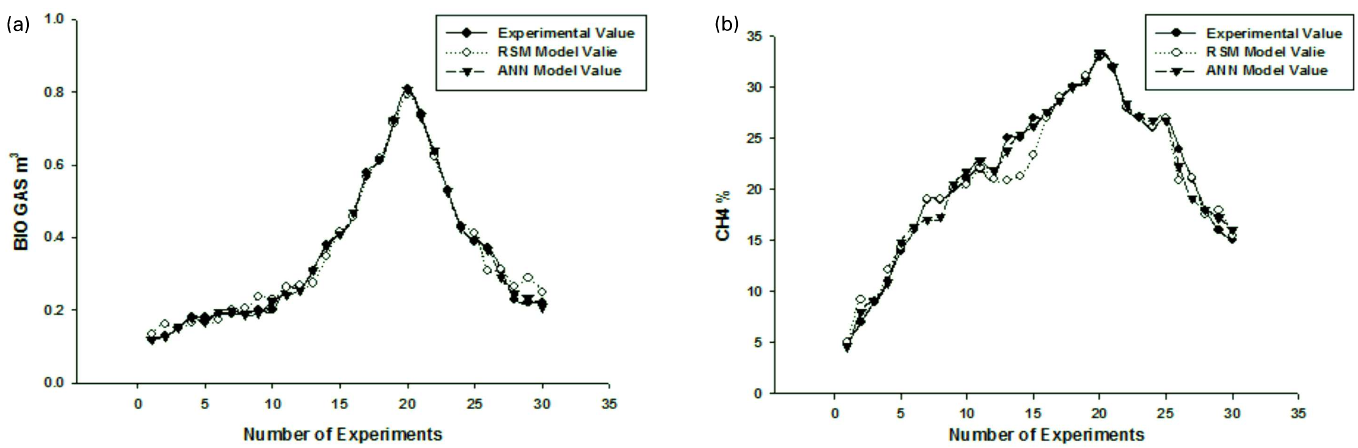

Figure 6. *RSM and ANN model values vs experimental result for (a) biogas and (b) methane*

tation time for biogas decreases simultaneously within a narrow pH range. The period of high hydro retention time and low pH range in biogas is shown in figure 3c to coincide with low levels of both variables. Surface contour chart for methane (CH_4) is shown in figure 4. In figure 4a, CH_4 is at its lowest at mesophilic temperatures, increases with rising mesophilic temperatures and remains constant across all levels of organic loading rate. Figure 4b shows that although CH_4 is highest at low agitation times, pH range of CH_4 is lowest. Hydro retention time and CH_4 concentrations are lowest in the low pH range and highest in the extended high pH range (Figure 4c).

3.1 Modelling for artificial neural network

In this study, the RSM approach was used to select a total of 30 training iterations for the neural network. 50%, 60% and 70% of the total data were used for training, while remaining data were used for testing and validation. Variation in biogas and methane (CH_4) data values for different trained data percentages shows that performance of the biogas plant can be predicted using the 60% trained data because the values are fairly similar to the experimental data. The error was found to be in the 10% range after comparing experimental data to the ANN-developed predicted values for 60% trained [15]. For both biogas and CH_4, figure 5 show the difference between expected and measured values, as well as degree of uncertainty for each experiment run.

3.1.1 Regression analysis for RSM and ANN: We compared the predictive abilities of the developed RSM and ANN models. To create these models, we validated them using 30 factorial data sets. Figure 6 show how experiments validated the ANN and RSM models for biogas and CH_4. The ANN model exhibits a lower percentage

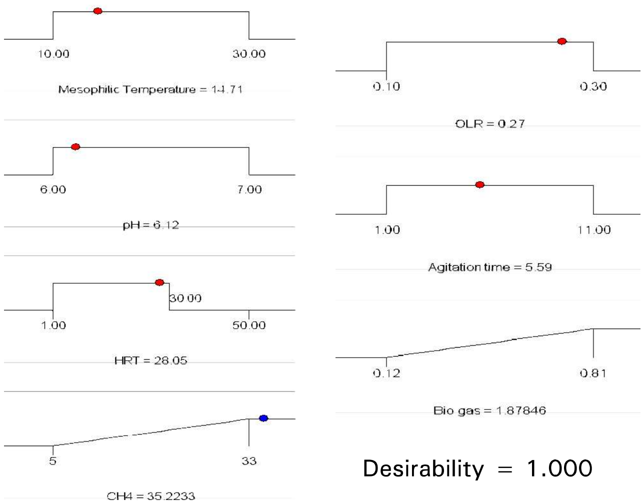

Figure 7. *Plot for ramp function on biogas plant*

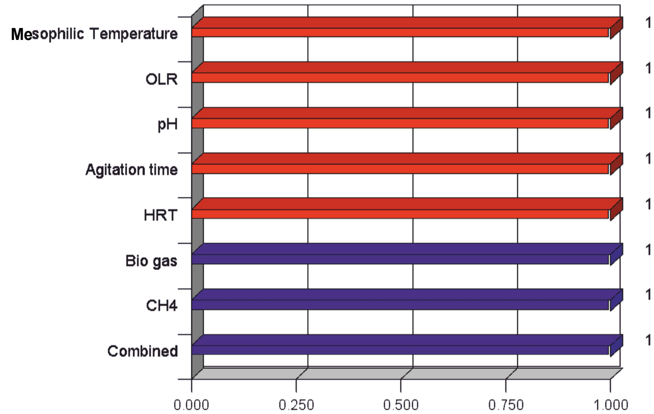

Figure 8. *Desirability bar graph for the biogas plant*

of variation compared to the RSM models, as evidenced by the higher R^2 and predicted R^2 values.

3.1.2 Numerical optimization: A biogas plant should be optimized to produce the highest-quality biogas and CH_4 while maintaining a low mesophilic temperature [16]. The optimal ratio of OLR, pH, agitation duration and HRT was determined by comparing the values to the desired outcomes [17]. It was found that parameter values close to 1 unit were appropriate for biogas and CH_4. Figure 7 shows the desirability bar graphs and ramp functions. Figure 8 displays ideal configuration for biogas and CH_4. Mesophilic temperature of 14.71 °C, OLR of 0.27, pH 6.12 and HRT of 28 hr are the optimal values for the input parameters, as indicated in figure 8. The graph depicts a function of overall preference for the responses given. The response's attractiveness is measured on a scale from 0-1 depending on how well it meets the goal. Closeness to 1 indicates higher predictive power. Each variable's adherence to criteria is shown as a bar on the graph.

3.2 Studies for the confirmation experiments

Numerical optimization is used to determine the best input parameter combination for increasing biogas plant productivity, as shown by Parthiban *et al.* (2021) [18]. Confirmation testing verifies that the identified optimal configuration for various quality metrics is accurate. The experiment's findings also support the response parameter. The experimental values for biogas and CH_4 are displayed in table 2. The observed values align closely with the optimized values, with a variation of only 0.1%, indicating significant improvement through numerical optimization.

Table 2. *Result of conformation test*

Parameters	Biogas	Methane
Optimum range	1.875	35.22
Conformation test value	1.879	34.929
Deviation (%)	0.0998	0.1008

4. CONCLUSION

This manuscript discusses biogas generation from vegetable waste, an emerging pollutant in central market of Chennai, India. The process of biogas production was optimized using an effective response surface methodology (RSM) combined with ANN to enhance the biogas plant's performance. Variables analyzed for biogas and CH_4 production included temperature, organic loading rate (OLR), pH and hydraulic retention time (HRT). The study found that the mathematical model based on RSM effectively predicts the biogas and methane output. The difference between experimental data and model predictions, within a 95% confidence level, confirms the model's accuracy. Optimal parameters were identified as mesophilic temperature of 14.71 °C, OLR of 0.27, pH of 6.12 and HRT of 28 hr, with biogas production of 1.875 m^3 and CH_4 percentage in the desirable range of 0.95. For neural network training, 60% of experimental data from the RSM design was used, showing good agreement between ANN predictions and experimental results within a 5% margin of error. Using a 5-10-2 feed-forward and feedback neural network, predictions of CH_4 and biogas generation were achieved. The comparison between experimental values, ANN predictions and RSM estimates showed high agreement, with errors less than 5%. Overall, the ANN model outperformed the RSM model in this study. Both ANN and RSM models can effectively predict biogas and CH_4

characteristics in biogas facilities. Confirmation studies indicate that the numerical optimization aligns closely with experimental data, with variation less than 0.1%. Therefore, using digester temperatures in mesophilic range to process vegetable waste is one of the best strategies to enhance biogas and methane yields.

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